ALTERING HYDROLOGIC REGIME

TO REVEGETATE CRUSTED SOILS ON SEMIARID RANGELAND

A Thesis

by

AMY LEIGH WENTZ

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2004

Major Subject: Rangeland Ecology and Management

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Approved as to style and content by:

Steven Whisenant (Chair of Committee)	Kevin McInnes (Member)
Bradford Wilcox (Member)	Steven Whisenant (Head of Department)

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ABSTRACT

Altering Hydrologic Regime to Revegetate Crusted Soils on Semiarid Rangeland.

(August 2004)

Amy Leigh Wentz, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Steven Whisenant

Dysfunctional rangelands lose nutrients and material faster than they capture or create them. The objective of this study was to determine the effectiveness of contour furrows, drill seeding, and aeration treatments in capturing overland flow, concentrating resources, and establishing perennial bunch grasses to convert dysfunctional semiarid rangeland to a functional rangeland. The site, located on the Edwards Plateau in west Texas, USA, had bare, structurally crusted soils with sparse short-grasses (*Scleropogon brevifolius*). The site had a low infiltration rate contributing to excess overland flow and loss of nutrients, organic matter, and soil. Contour furrows were installed with varying intra-furrow distances (0.6 to 61 m) and then broadcast seeded to determine if furrow spacing would produce a vegetative response. Portions of the intra-furrow areas were aerated and drill seeded. All seed mixes contained warm season, perennial bunch grasses (*Bouteloua curtipendula*, *Leptochloa dubia*, and *Setaria leucopila*). Soil beneath furrows had greater soil water content (p-value < 0.05) than intra-furrow areas. Furrow plots had greater density of seeded grasses and total vegetation (19 individuals m^{-2} and 191 individuals m^{-2}, respectively) than intra-furrow plots (0 individuals m^{-2} and 89 individuals m^{-2}, respectively). This study supports other findings that suggest 1.5 m to 1.8 m is optimum intra-furrow spacing. Vegetative responses to drill seeding and aeration treatments were insignificant. Observations suggest that contour furrows are effective at establishment and support of perennial vegetation by capturing and retaining water that otherwise would be lost to runoff from untreated soil.

Dedicated to the inner peace that every individual should receive from gazing upon a star or flower.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Rangelands contribute to the world's biodiversity, supply a growing human population with areas for pastoralism, tourism, and hunting, and provide much of the water for agricultural and urban uses (Ludwig et al. 1997; Whisenant 1999). It is clear that sustainability of many rangelands is not possible under current management practices. Many rangelands are dysfunctional – they lose materials faster than they capture or create them (Ludwig et al. 1997). Overgrazing combined with drought are primary factors that have lead to disfunctionality.

Losses in dysfunctional landscapes occur through erosion and degradation processes and result in decreased vegetative cover. Loss of vegetative cover may enhance erosion and degredation, creating a positive feedback whereby less vegetation cover is produced in the next cycle. Positive feedback degradation cycles are difficult to reverse. As the degradation cycle progresses, the biotic processes affecting hydrologic processes slowly give way to abiotic or geophysical processes. Once geophysical processes are driving the system, many landscapes lose the ability to repair themselves and require human intervention to return to a resource capturing and productive state (Whisenant 1999; Archer & Stokes 2000).

Thurow (1985) states that total organic cover is the most important factor influencing infiltration rate on the Edwards Plateau, Texas. In place, organic cover serves as biotic control of the system. Once organic cover is reduced to a sparse or nonexistent state, abiotic processes take control of the system. Raindrops falling on bare soils break down soil aggregates, and the resulting dispersed soil particles clog pores and create structural crusts. These crusts have a greater bulk density and narrower pores than the underlying soil — characteristics that reduce the rate water infiltrates into the soil, even if the crust is thin and the underlying soil is otherwise highly permeable (Hillel 1998). At the plot scale, crusts decrease soil moisture content and depth of wetting front (Patrick 2002). On a watershed scale, crusted soils produce a high percentage of runoff, leading to increased overland flows and less water captured and stored in the soil for vegetative growth. These problems contribute to the positive feedback cycle. Aside from climatic

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This thesis follows the style and format of Restoration Ecology.

changes, the only means of reversing the degradation cycle is to introduce management practices to capture and retain water (Whisenant 1999).

Alternative strategies for capturing and retaining water include seedbed manipulations to increase local infiltration (minimize runoff) and topographical manipulations to capture runoff. If successful, both approaches retain enough water to establish and sustain vegetation. Increased vegetative cover initiates a positive feedback improvement mechanism where the additional vegetation leads to more water being retained, which in turn results in more vegetation. These two water capturing strategies have important differences. Seedbed treatments attempt to hold the precipitation as close to where it falls as possible, with the goal of complete vegetation coverage. In contrast, runoff harvesting has the goal of initially establishing vegetation only on a portion of the surface. The advantage of runoff harvesting is that the risk of failure from the lack of sufficient water to establish vegetation is diminished. Thus, designing strategies to capture and retain water becomes a compromise between diminished risk and percentage of the site that is initially revegetated.

This study evaluates the effectiveness of two seedbed manipulations to increase local infiltration, aeration and drill seeding, and one runoff harvesting technology, contour furrowing, in increasing retained precipitation and vegetation density on a semiarid, structurally crusted rangeland.

Background and Relevance

Water harvesting for rangeland improvement in the U.S. has been in use for nearly a century (Branson et al. 1966; Wight 1975). Half of the technologies described by Wight (1975) (contour furrowing, pitting, and contour terracing) were implemented in the 1930s, with the remainder (level bench terracing, gully plugs, ripping, and chiseling) in use by the 1970s. In general, the goals of reducing erosion and runoff were achieved. Benefits include reduced soil salinity (Branson et al. 1966; Shanan et al. 1970; Soiseth et al. 1974), increased plant biomass (Branson et al. 1966; Slayback & Cable 1970; Fisser et al. 1974; Soiseth et al. 1974; Neff & Wight 1977; Wight et al. 1978a; Wight et al. 1978b; Suleman et al. 1995), altered species composition to increase forage species (Wight et al. 1978a), and establishment of woody species (Shanan et al. 1970; Whisenant et al. 1995).

Design of water harvesting technologies must consider specific watershed factors including slope, climate, precipitation intensity, litter, vegetation, and soil texture, structure, and dispersivity. Water harvesting is most effective in arid and semiarid lands with low infiltration rates and sparse vegetation. Fine to medium textured soils with poor structure and crusted surfaces are prime candidates for runoff harvesting due to their lower infiltration rates (Branson et al. 1966; Wight et al. 1978a; Wight et al. 1978b). For water harvesting strategies to be considered, Ludwig et al (1995) suggest the slope of the land be > 1%. Precipitation intensity must also be great enough to produce runoff.

Seedbed manipulations, including mechanical soil aeration, typically have a goal of complete vegetation coverage. On the Edwards Plateau, pitting the soil surface to retain water (i.e. aeration) has been more effective on upland soils than finer textured soils of *Hilaria mutica* (tobosa) flats (Barnes et al. 1958). On compacted, shallow, stony soil in an area of relatively high rainfall in Wales, slitting pasture surface doubled net accumulation of herbage (Davies et al. 1989). However, slitting aeration did not affect vegetation yield on loamy pasture or hayland in central Alberta, Canada (Malhi et al. 2000). Overall benefits noted by Barnes et al. (1958) in the Great Plains and Southwest desert area include improved infiltration rate, increased moisture penetration, grass establishment, and increased perennial grass production.

MATERIALS AND METHODS

Study Area

The study area is located on the Big Jim Ranch, 10.3 km north of Big Lake, in Reagan County, Texas, USA. This area lies in the semiarid portion of the Edwards Plateau of western Texas (31°16’ N, -101°32’ W). Big Jim Ranch has been used for livestock production since at least 1897. Cattle, sheep, and horses are stocked on the ranch, although they were excluded from the study area after installation of the treatments. The location of the research site on the Ranch was selected because the area was in a degradation cycle and the crusted state of the soil and landscape topography were favorable for effective water harvesting treatments to reverse the degradation cycle.

Reagan County’s mean annual temperature is 17.2 °C, with a mean frost-free period of 237 days. Mean annual precipitation from 1940 through 2002 is 455 mm. Annual precipitation totals for this time period vary from 231 mm to 864 mm, with a median of 446 mm. Mean annual pan evaporation for the county is 1753 mm, considerably higher than annual precipitation. Precipitation distribution is bimodal, with fifty percent of the precipitation falling during the four months of May-June and September-October. Pan evaporation for these two periods is 385 mm and 294 mm, respectively (Texas Water Development Board 2002).

The study site lies on deep, calcareous silty clay loam of the Reagan series (fine-silty, mixed, superactive, thermic, Ustic Haplocalcid) and is characterized as a loamy range site. This soil has a moderate water capacity in the surface and is underlain by alluvium, including caliche locally covered by silt (University of Texas 1974; USDA 2003). Slopes in the site of the treatments are < 3%. Site elevation is approximately 793 m. The initial infiltration rate was determined to be approximately 0.06 mm s^{-1} and the steady state infiltration rate was determined to be approximately 0.02 mm s^{-1}. Average 30 min precipitation intensities ranging from 0.13 to 0.65 mm s^{-1} were measured in September and October 2002. Therefore, rainfall intensities are great enough to produce runoff.

Hilaria mutica, *Bouteloua curtipendula* (sideoats grama), *Panicum obtusum* (vinemesquite), and *Buchloe dactyloides* (buffalograss) are indigenous to the area. *Scleropogon brevifolius* (burrograss) is an increaser, while *Prosopis glandulosa* (mesquite) invades and persists under grazing pressure. Under grazing pressure, increaser species increase in relative coverage for a time and may eventually decrease (Dyksterhuis 1949).

Treatment areas were selected based on local topography, *P. glandulosa* density, and edaphic conditions. Given the crusted state of the bare soil, it was apparent that 1% to 2% slope was sufficient to produce runoff from a moderate precipitation event. Lower *P. glandulosa* density was selected for ease in tractor movement and greater consistency of plot characteristics.

Experimental Design

The treatments were set up in a randomized complete block design. Each of the four blocks contains four runoff harvesting contour furrows with varying source areas. The length of each furrow was quartered and the respective catchment source was treated with one of four treatments.

Contour furrows 15 to 30 cm deep, 100 to 180 m long, and 0.7 to 1.8 m wide were created with a D5 bulldozer in June 2001. Treatments were applied to four replicate blocks, each block having four furrows. Within each block, the fetch above a furrow was approximately 1 m, 4 m, 11 m, or determined variably by the furrow's position in relation to the watershed boundary (see Figure 1; Note: All tables and figures cited in the text are located in Appendix A.). (Although difficult to determine in the field, the fetch above the most upslope furrow of each block was estimated to be 61 m.) This resulted in catchment to basin ratios (cbr) varying from 2:1 to 55:1. The fetch of each plot was measured individually and used as a covariate in the statistical analysis. The pattern of varying fetch of approximately 1, 4, 11, or 61 m and the rank of each of these within a block is confounded. Accordingly, the furrow with approximately 1 m fetch is the most downslope furrow in each block. The length of each furrow was divided into four equal sections, with each section of runoff source area receiving a different treatment. The placement of the four treatments along the source area of each furrow was randomized, with each treatment occurring once along each furrow.

The fetch above each furrow section was aerated with an AerWay agricultural aerator (creating approximately 8 x 8 x 8 cm pits) and drill seeded with a Truax Flex II Grass Drill (6 rows spaced 20.3 cm apart), drill seeded, or not treated (see Figure 2). Aeration treatments vary in their application date (June 2001 or March 2002). The four catchment area treatments are drill seed only (D), drill seed and aeration 2001 (DA1), drill seed and aeration 2002 (DA2), and no treatment (N). Drill seed treatments were applied March 2002. Furrows were broadcast seeded in June 2001. Broadcast seeding rates varied from 11 to 22 kg ha^{-1}. Both drill and broadcast seed mixes consisted of *B. curtipendula* (60% by weight), *Leptochloa dubia* (green sprangletop) (10% by weight), and *Setaria leucopila* (plains bristlegrass) (30% by weight). These native, warm season, perennial grasses are categorized as good for cattle grazing and good to fair for wildlife grazing (Gould 1978; Hatch & Pluhar 1993).

Although the furrows were broadcast seeded, for statistical analysis the furrow plots were labeled with their upslope counterpart's treatment. Due to the structure of the experimental design, the upslope plots could influence the output of the furrow plots (For example, drilled seed could wash into the furrows or drill seed and/or aeration microtopography could facilitate the infiltration of rainfall that would otherwise runoff into a furrow plot.).

The original goal was to make the shortest fetch approximately 2 m. However, after creation of the furrows the shortest fetch was approximately 0.6 to 1 m. This was due to the culmination of several factors, including curvature of contour lines, buried boulders, and *P. glandulosa* trunks affecting the maneuverability of the dozer. These furrows were broadcast seeded just as the remaining furrows. However, the fetch of these furrows could not be easily drill seeded or aerated and therefore the fetch was not treated. A decision was made not to collect vegetation data from these furrows. However, one soil moisture measuring device (described below) was installed in one of these furrows and empirical observations of the vegetation response are included in the Discussion.

Soil Moisture Measurements

Soil moisture was measured using Delta-T Devices' Profile Probe (model PR1/4) and Campbell Scientific's Water Content Reflectometer (WCR) (model CS615). Both instruments measure the bulk dielectric constant of soil and relate it to volumetric soil water content. The PR1/4 is a handheld composite rod approximately 2.5 cm in diameter and 50 cm in length. Access tubes for the PR1/4 were placed in the soil for the duration of the project and the PR1/4 was carried from plot to plot. The PR1/4 measures volumetric soil water content at depths of 9 cm, 19 cm, 29 cm, and 39 cm. At each depth 95 % of the volume of soil influencing the probe's readout is located within a cylinder of soil 8 cm high with a radius of 10 cm surrounding the probe (Delta-T Devices 2001).

The PR1/4 was used periodically, from May 2002 through March 2003, to characterize the soil moisture after precipitation events and to compare volumetric soil water content beneath the furrows and upslope of the furrows. Water content at the surface was assumed to be the same as the 5 to 13 cm soil layer. In addition, the water content for the underrepresented layer of soil between each profile measurement was linearly interpolated from its closest neighbors. The volumetric water contents were then multiplied by their respective proportion of total depth and summed to create a single cumulative value for analysis. Data from the Profile Probe were analyzed as "surficial" water, 0 – 13 cm, and as "total profile" water, 0 – 43 cm. The surficial water was estimated as it has a direct influence on germination and seedling establishment. The total profile water was included to investigate the full water harvesting capabilities of the furrows. Due to the limited number of plots in which data were collected with the Profile Probe (14 upslope and 14 furrow plots), the block effect and upslope treatments were not entered into the statistical models. To compensate for PR1/4 sensitivity to clay content, a multiplication factor of 0.612 was applied to the factory calibration. This factor is a ratio of the approximate maximum recorded value (0.735 m^3 m^{-3}) and the maximum expected value (0.45 m^3 m^{-3}) under saturated conditions. The furrows held ponded water for more than a day on several occasions and this was the basis for the values chosen to create the scaling factor.

The CS615 consists of 2 steel rods connected to an epoxy head. The rods are 3.2 mm in diameter, 30.0 cm in length, and spaced 3.2 cm apart (Campbell Scientific, Inc. 1996). The volume of soil influencing a CS615 reading is an ellipse with a major diameter of 8.5 cm and a minor diameter of 5.0 cm along a length of 30 cm (J. Ritter 2004, Campbell Scientific, Inc., Logan, UT, personal communication). CS615s were inserted into the soil in March 2002 at a 45° angle to the land surface. They were configured to measure the average volumetric soil water content every hour from a depth of approximately 3 to 24 cm. This data was recorded on a Campbell Scientific datalogger (model CR10X). To compensate for

CS615 sensitivity to clay content, a multiplication factor of 0.56 was applied to the factory calibration. This factor is a ratio of the approximate maximum recorded value (0.8 m^3 m^{-3}) and the maximum expected value (0.45 m^3 m^{-3}) under saturated conditions. The furrows held ponded water for more than a day on several occasions and this was the basis for the values chosen to create the scaling factor. Due to CS615 sensitivity to temperature fluctuations, graphical output represents the values recorded at midnight to remove artificial diurnal trends. This data was used to compare volumetric water content beneath the furrows and in untreated, unfurrowed control plots.

Two Davis Rain Collector IIs and HOBO Event Loggers were placed at the study area. Each 0.254 mm of precipitation was time-stamped to 0.5 seconds.

Soil Characterization

Using a single-ring infiltrometer, infiltration rates were calculated on 10 upslope locations representing all blocks and all treatments. The average initial infiltration rate was reported as the geometric mean. The saturated hydraulic conductivity (K_s) was approximated by the steady state infiltration rate (Hillel 1998) and also reported as the geometric mean. Prior to infiltration tests, mean gravimetric water content of the soil was 0.02 kg kg^{-1} and 0.04 kg kg^{-1} for the 0 to 5 cm layer and 5 to 10 cm layer, respectively.

The water holding capacity (WHC) at -33 kPa water potential was determined at soil depths of 0 to 5 cm, 5 to 15 cm, 15 to 25 cm, 25 to 35 cm, and 35 to 43 cm. The WHC at -1500 kPa water potential was determined for the 0 to 5 cm soil layer. WHC analysis was conducted on all plots containing the profile probe access tubes following the methods of (Dane & Hopmans 2002).

The slope of each plot was quantified with a Suunto Optical Reading Clinometer (PM-5) as it lay on a 1.1 m long board. The clinometer and board lay on the ground, perpendicular to the topographic contour, on three to six locations per plot. The values were averaged and used as a covariate in the statistical analysis.

Vegetation Measurements

Vegetation response was measured using square 0.10 m^2 quadrats during June 2003. In each quadrat, individual plants were identified to genus, or species if known, and counted. Three quadrats were used to quantify the density of vegetation in each plot within the contour furrows. All furrow quadrats were placed on the deepest part of the furrow (the area in which the broadcast seeds likely established). Upslope vegetation appeared to have a slight trend of increased density closer to the furrow. To take this into account, a coordinate system was used to determine the placement of 10 quadrats in the upslope portion of each plot.

Statistical Analysis

Soil moisture and water holding capacity were analyzed using a general linear model analysis of covariance (ANCOVA) and analysis of variance (ANOVA), respectively. Levene and Kolmogorov-Smirnov or Shapiro-Wilk's tests were used to confirm normality and homogeneity of variance of all ANCOVA and ANOVA models. Soil moisture data for the upper 13 cm and for the upper 43 cm were transformed with natural log to meet the assumptions of ANCOVA. However, the results of the ANCOVA were the same on the transformed and untransformed data. Therefore, the untransformed values are reported. The water holding capacity data did not require transformation.

Vegetation density was analyzed using a general linear model ANCOVA. For density analysis, vegetation was grouped into two categories: total density (all vascular plants) and seeded density (grasses that were seeded into the plots: *B. curtipendula*, *L. dubia*, and *S. leucopila*). Total and seeded density data were transformed with square root and square root +1, respectively, to meet the assumptions of ANCOVA. However, the results of the ANCOVA were the same on the transformed and untransformed data for the total vegetation analysis. Therefore, the untransformed values are reported. Vegetation frequency was analyzed using nonparametric Kruskal-Wallis and Spearman's rho. All post hoc tests were performed on the transformed data, if transformation was required. However, for ease of interpretation, all data points, box and whisker plots, means, and confidence intervals reported in the text and graphs represent the untransformed data.

RESULTS

Soil Moisture

Contour furrows effectively harvested runoff water. Variables included in the statistical model of the Profile Probe data and their significance are in Table 1. The furrow location had significantly greater surficial water content than the upslope location (Figure 3). Subsoil beneath the furrows also held more moisture than their upslope counterparts (data not shown). Fetch was not significant in influencing soil moisture in the surficial profile. Although fetch was found to be a significant factor in the statistical model for the total soil profile, the slope of the linear relationship between fetch and volumetric water content of the total profile was only slightly positive (Figure 4). For both soil profiles, slope and soil moisture were inversely related (Figures 5 and 6).

WCR measurements provided insight into the hydrological mechanics of the study area. Furrows were successful in harvesting runoff from intense storms. Control plots did not capture this runoff water. Rainfall events of high intensity and long duration (≥ 30 min) led to increased furrow soil moisture while not increasing control plot moisture (Figure 7). The furrow plots held this moisture for many days. For example, the water content of the furrows was higher than that of the control plots for 7 d following an event totaling 6.6 mm. More importantly, the furrows had higher water content for 85 d following 2 events totaling 39.4 mm. Monthly precipitation during the study and long-term monthly medians are shown in Figure 8.

The WHC at -33 kPa of the 0 to 5 cm layer and the 25 to 35 cm layer was significantly greater in the furrows than in the upslope area, as was the WHC at -1500 kPa water potential for the 0 to 5 cm layer (Table 2).

Vegetation

The water harvested by the furrows supported the establishment of perennial bunch grasses and opportunistic forbs. The drill seeding and aeration treatments were not successful in establishing perennial bunch grasses. The effectiveness of the furrows, fetch, and drill seed and aeration treatments and the influence of slope on vegetation establishment were evaluated by analyzing vegetation density and frequency.

Variables included in the statistical model analyzing vegetation density and their significance are in Table 3. Location (upslope or furrow) was the most statistically and ecologically significant factor influencing total vegetation density and the density of seeded grasses, with the furrow location having the greater density (Figure 9). Independently, slope and fetch did not significantly influence vegetation density. The interaction of location and slope were different for total vegetation density and density of seeded grasses. In both cases, density of the upslope plots did not change with changes in slope. However, the total vegetation density in the furrow plots decreased with increasing slope while density of seeded grasses of the furrow plots increased with increasing slope (Figures 10 and 11).

The drill seeding and aeration treatments significantly influenced seeded density as they interacted with fetch. As fetch increased, there was a decrease in the density of the seeded grasses on the DA2 plots. Fetch did not influence seeded grass density on the D, N, or DA1 plots (Figure 12). Although treatment was significant as a main effect, the Bonferroni means separation test did not determine any means to be significantly different. Therefore, significance of treatment as a main effect is attributed to the presence of the significant treatment * fetch interaction.

Five grasses and four forbs that occurred on the greatest number of plots were chosen for frequency analysis (Table 4). *Scleropogon brevifolius* was the only species with a significantly greater frequency in the upslope plots, while the remainder of the species with significantly different frequencies was more frequent in the furrow plots. Upslope treatments, fetch, and slope did not significantly influence the frequency of any of the nine species analyzed.

DISCUSSION

Once landscapes cross a critical threshold and abiotic conditions control the flow of water, revegetation is not likely to occur simply by removing grazing or other pressures. Water harvesting structures such as contour furrows provide an opportunity to interrupt the abiotic control of hydrologic processes and allow biotic processes to regain some control. Contour furrows harvested runoff and supported the establishment of perennial bunch grasses and opportunistic forbs. The drill seed and aeration treatments and the variation of fetch and slope in this experimental design did not play an important role in harvesting runoff or establishing vegetation.

The water holding capacity of the 0 to 5 cm layer was significantly greater in the furrows than the upslope plots. This alone did not provide the furrow plots with the advantage needed to retain more soil moisture or support more vegetation than the upslope plots. The high percentage of runoff on the upslope plots does not allow the soil to absorb enough moisture for the soil to attain its water holding potential. The upslope plots are typically much drier than the furrow plots and therefore the WHC differences would produce negligible effects.

The lack of strong significant conclusions of the influence of fetch from the ANCOVA models and post hoc regression indicate that the scale of fetch in this experimental design was predominately too great to see a strong positive correlation between fetch and soil moisture or vegetative response. The fetch that produced the greatest vegetative yield per ha is approximately 3.5 m. In this experimental design, that correlates to a cbr of approximately 2:1 to 4:1. However, it must be noted that these numbers are in reference to the largest three of the four fetch lengths created. The smallest catchment had a fetch of approximately 1 m and a cbr of approximately 1:1. Again, the furrows with 1 m fetch had empirically similar vegetative responses to the remaining furrows and the single WCR placed in such a furrow followed the same trend of soil moisture response to that of the remaining furrows. These findings support studies that suggest 1.5 m to 1.8 m is an optimum intra-furrow spacing (Branson et al. 1966; Fisser et al. 1974; Soiseth et al. 1974; Wight 1975; Wight et al. 1978a; Wight et al. 1978b).

Given the crusted state of the soils and limited topographic variation of the landscape (0 – 3 % slopes) we were not able to observe a strong positive correlation between slope and soil moisture or vegetation responses.

Drill seeding and aeration treatments both initially broke the crusts of the soil and provided microcatchments potentially to aid in establishment of the seeded grasses. However, the aeration pits filled with soil after the first few rain events. The limited microtopography created by drill seeding was still evident 18 months after treatment. Neither the aeration nor drill seeding treatments were able to capture rainfall and instigate significant grass seed germination, much less support grass establishment. It appears that the scale and structure of these two treatments are not suited for the edaphic and climatic conditions present at the research site.

Bouteloua curtipendula germinates under conditions of relatively low water potentials of short duration (Emmerich & Hardegree 1996; Abbott & Roundy 2003). *Leptochloa dubia* also germinates readily. However, these warm-season grasses require approximately 9 to 21 d of available water to establish. Lengthy dry periods occurring after germination leave the seedling at high risk of fatality (Abbott & Roundy 2003). Although the water content of the WCR control plots increased after long, gentle rains, the moisture value represents an average of the moisture present in the 3 to 24 cm layer. It is likely that once the upslope plots or control plots became moist that the 0 to 2 cm layer (the layer most likely to influence germination and initial seedling establishment) would dry quickest.

The minimum scale and structure necessary for grass germination and establishment appears to be between that of the drill seed and aeration treatments and the 1 m fetch of the furrows described in the Experimental Design. One CS615 was installed beneath such a furrow. This furrow responded in the same pattern as the remaining furrows. In addition, empirical observations of the seeded grasses in these furrows showed that bunch grass density and height appeared to be as robust in these furrows as in their respective within-block upslope furrows.

Reports on the expected and measured longevity of furrows (through gained soil moisture and/or increased vegetative production) vary from 7 to over 25 years (Branson et al. 1966; Fisser et al. 1974; Soiseth et al. 1974; Wight 1975; Neff & Wight 1977; Wight et al. 1978a; Miyamoto et al. 2004). The variation in the life of furrows and their benefits is a function of many factors including soil erosion rates (filling the furrows with soil or eroding the berm of the furrow away), periods of drought, and precipitation patterns (intensity and duration). These factors may work together to support perennial vegetation and create a self sustaining cycle of increasing water harvesting capacity and increasing vegetation production. However, a drought that occurs before the vegetation and organic matter are established may break the cycle and leave the furrows susceptible to higher rates of erosion. Based on the rate of soil erosion (empirical observation) the furrows in this study will likely make the 7-year mark. How long the furrows last beyond that and when physical control of water is replaced by biotic control will likely depend on future weather patterns and stocking rates.

CONCLUSIONS

Contour furrows are a form of abiotic control that can be used to reestablish biotic control of landscape functions. Furrows retained moisture for a duration long enough to support seeded perennial bunch grasses and opportunistic forbs. The density and frequency of vegetation was significantly greater in the furrow plots than upslope plots. The aeration and drill seeding did not alter abiotic conditions enough to support bunch grasses or significant numbers of forbs. The influence of the variations in slope on soil moisture or vegetative response was inconclusive. The fetch length that will harvest the most water and produce the most vegetation per ha is between 1 and 3.5 m, which correlates to a cbr of 1:1 to 3:1. Most importantly, contour furrows provide a foundation in returning resource-capturing capabilities to dysfunctional semiarid landscapes.

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APPENDIX A

Figures

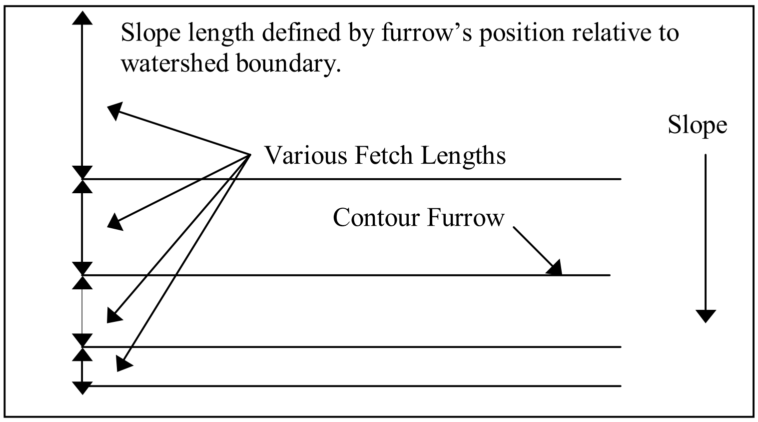

Figure 1. Block containing four contour furrows with various slope lengths (diagram not to scale).

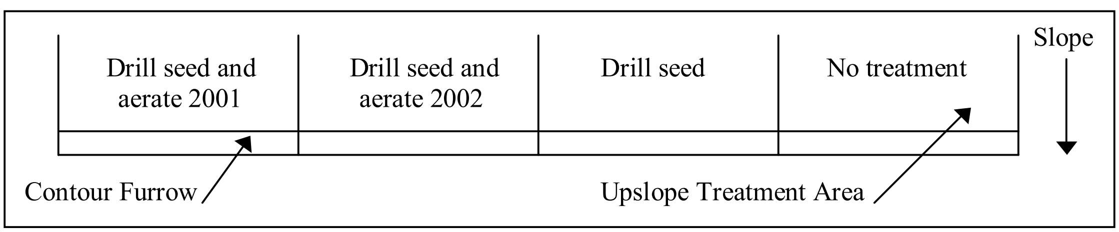

Figure 2. Contour furrow divided into four equal sections. Each section of furrow catchment area received a different, randomly assigned, treatment (diagram not to scale).

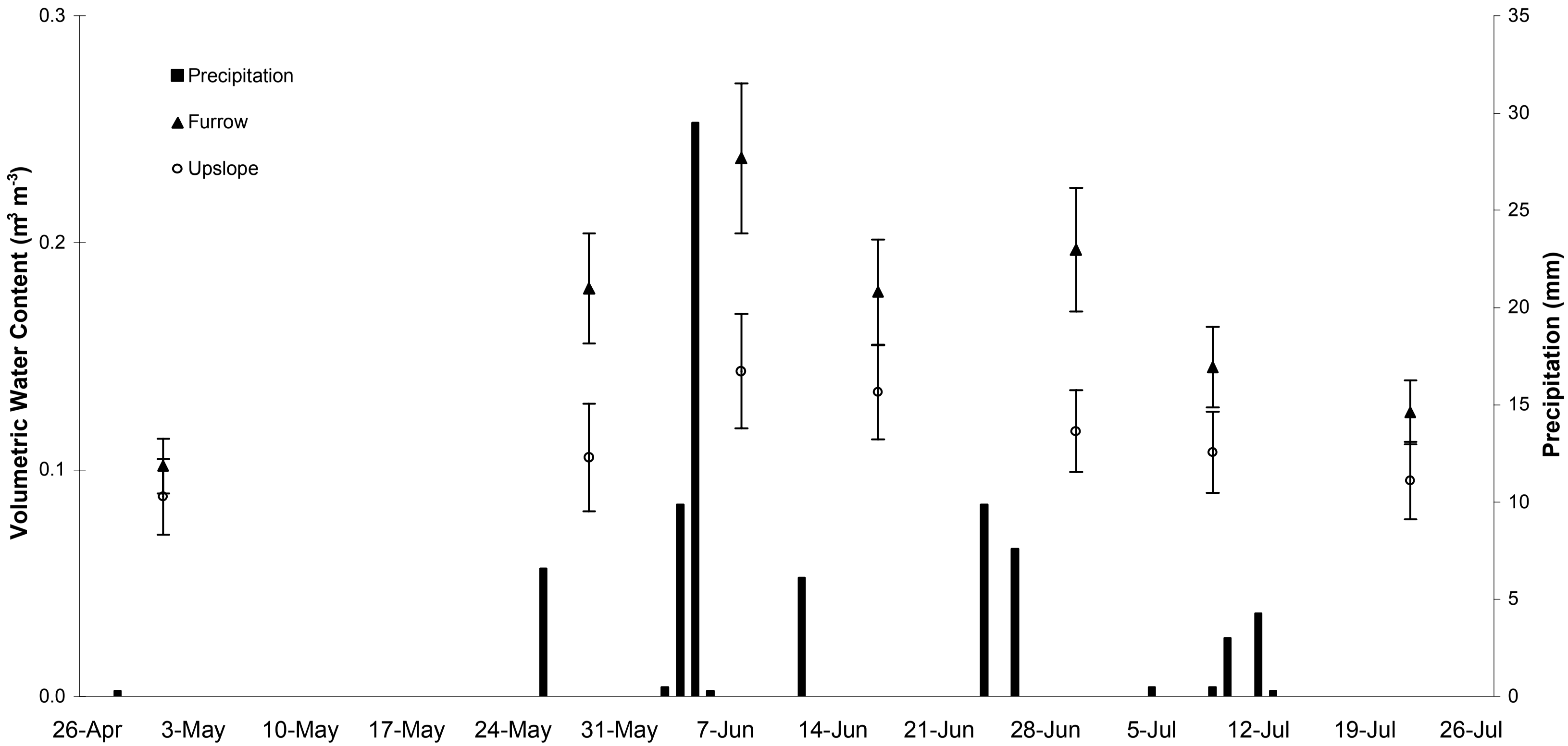

Figure 3. Mean volumetric soil water content of upper 13 cm in furrow and upslope plots calculated from Profile Probe data of 2002. Error bars represent 95 % confidence intervals. Research site located in Reagan County, Texas, USA.

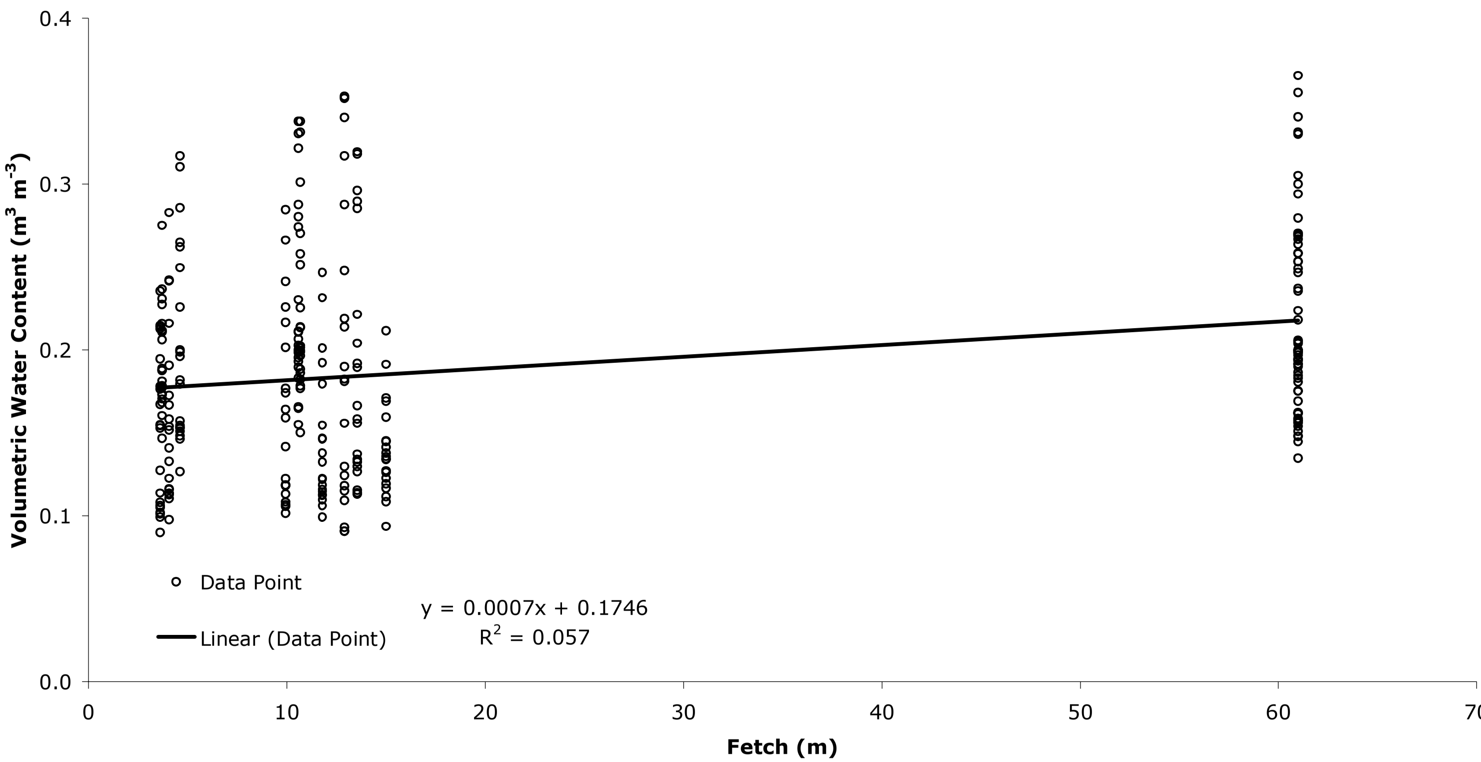

Figure 4. Fetch length influence on volumetric water content of upper 43 cm. Profile probe data. Research site located in Reagan County, Texas, USA.

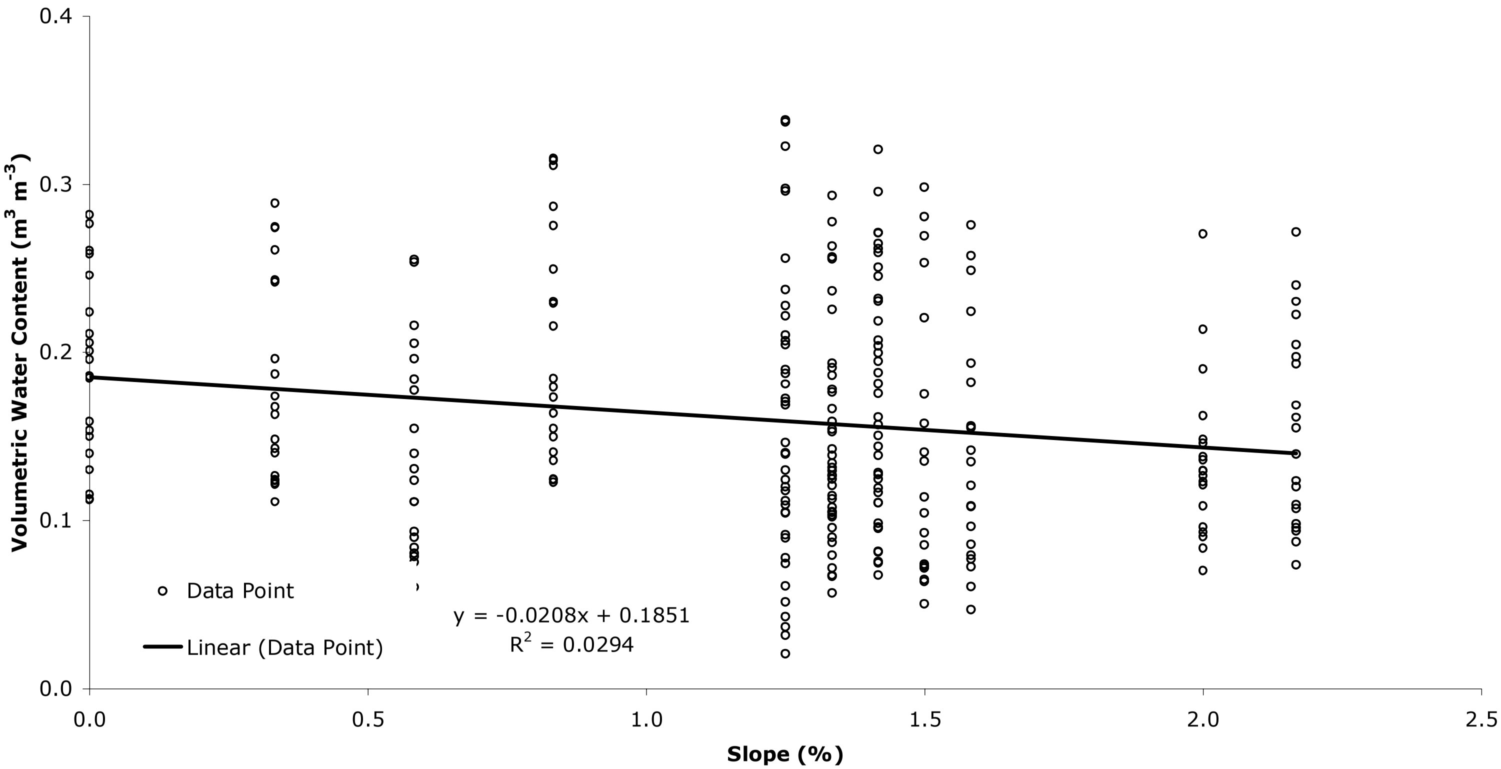

Figure 5. Volumetric water content of upper 13 cm plotted against the slope of the plot. Line represents best-fit line. Profile Probe data. Research site located in Reagan County, Texas, USA.

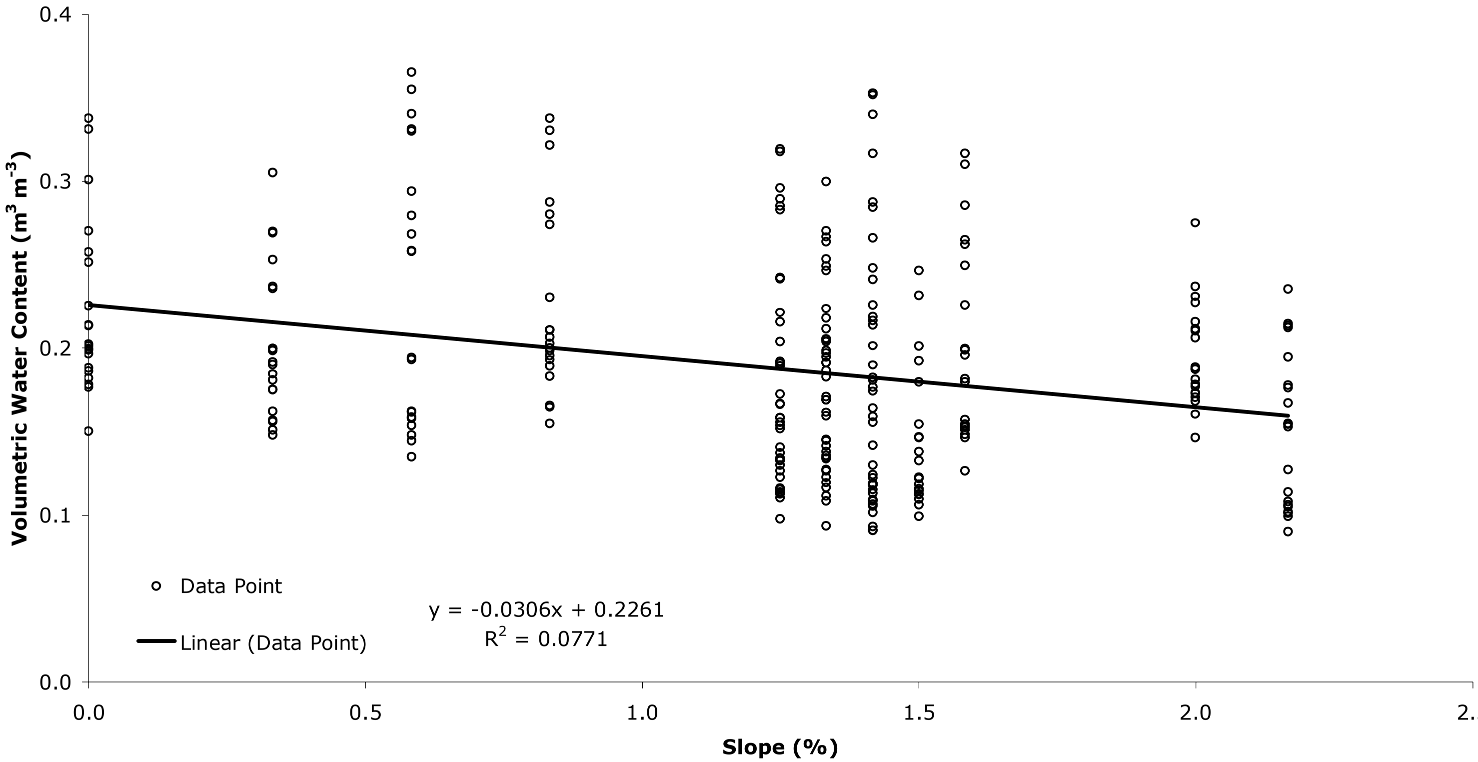

Figure 6. Volumetric water content of upper 43 cm plotted against the slope of the plot. Line represents best-fit line. Profile Probe data. Research site located in Reagan County, Texas, USA.

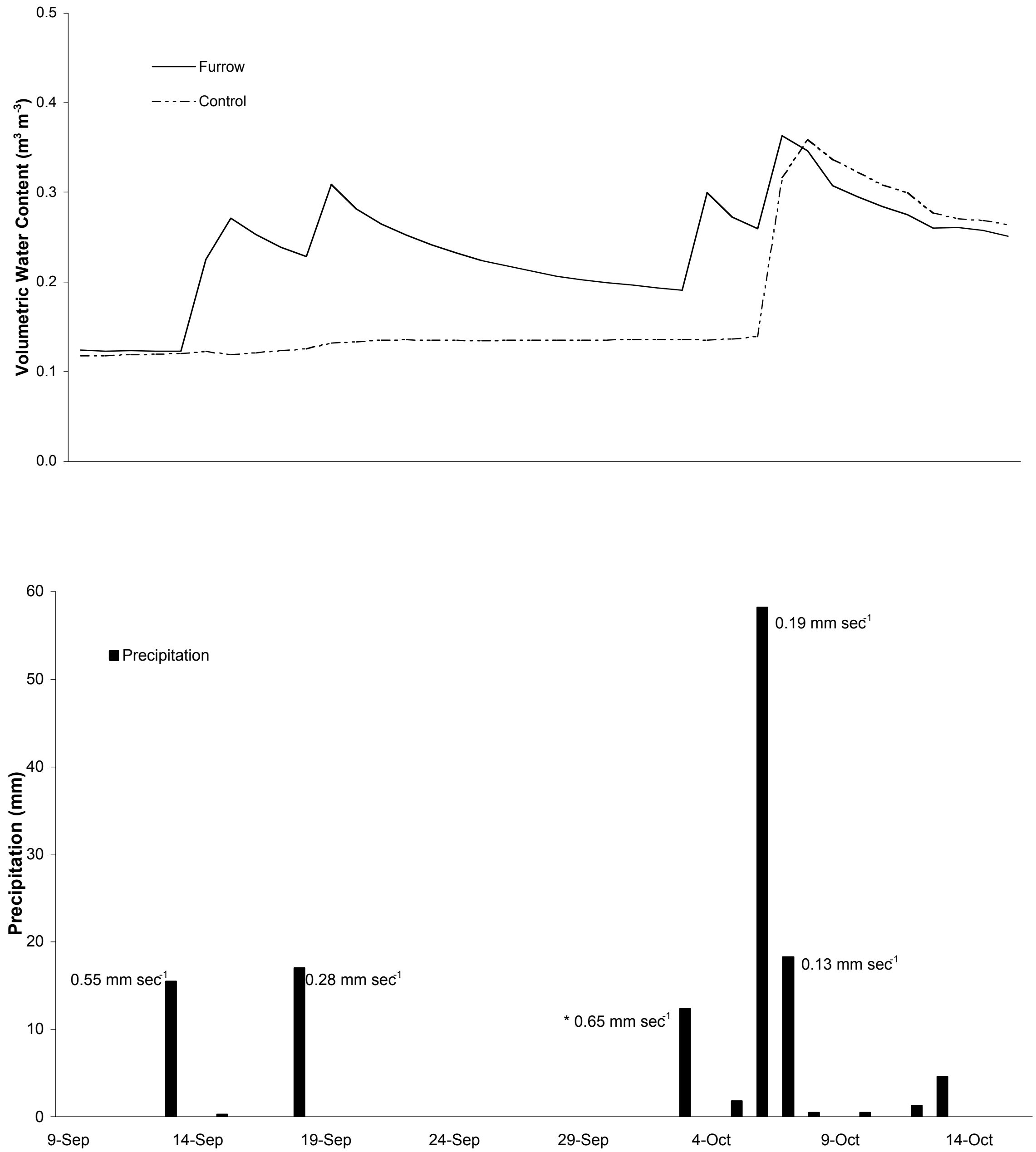

Figure 7. Mean response of midnight readings from CS615 sensors in upslope (n = 6) and furrow (n = 2) plots to varying precipitation quantities and intensities during 2002. Research site located in Reagan County, Texas, USA.

*This event was 18.75 min in duration. The remaining events whose intensities are described were ≥ 30 min.

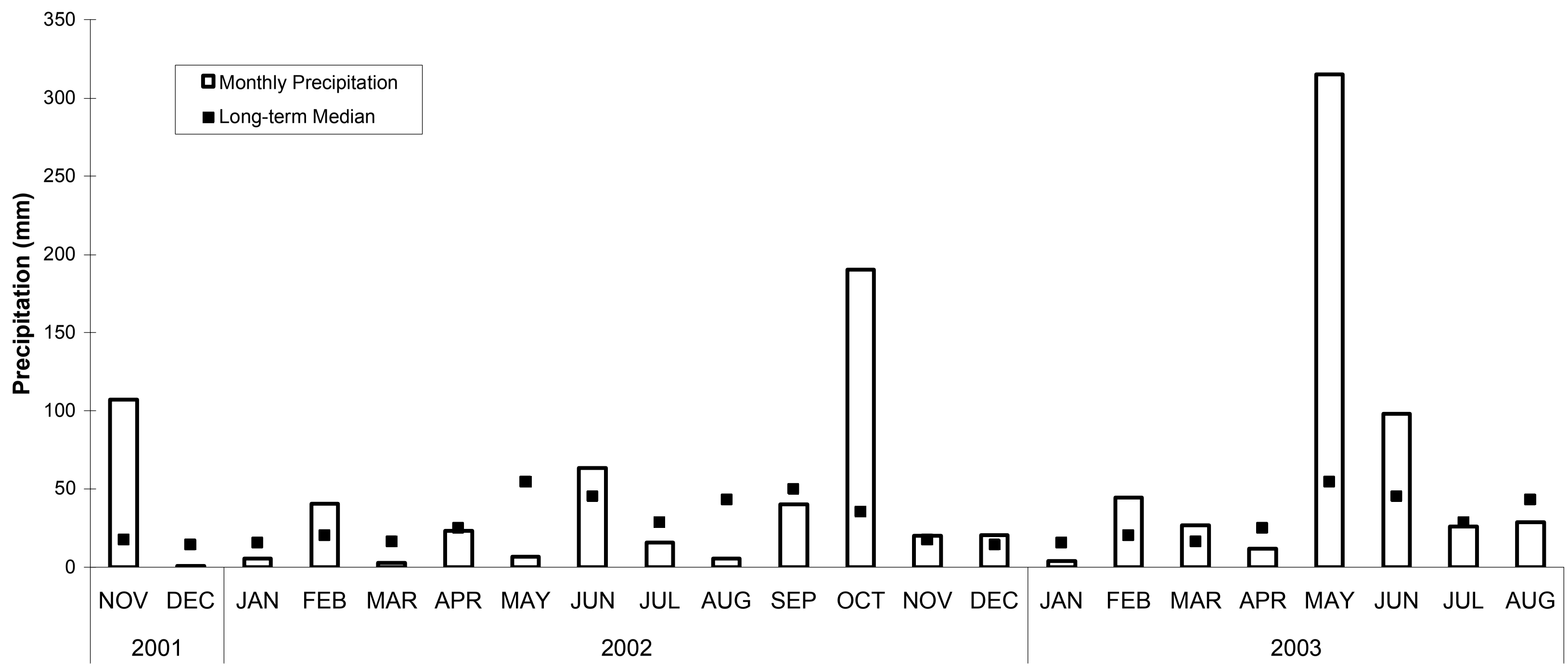

Figure 8. Actual and long-term median (62 year) precipitation for the study area (north of Big Lake, Texas) and Reagan County, Texas, USA, respectively.

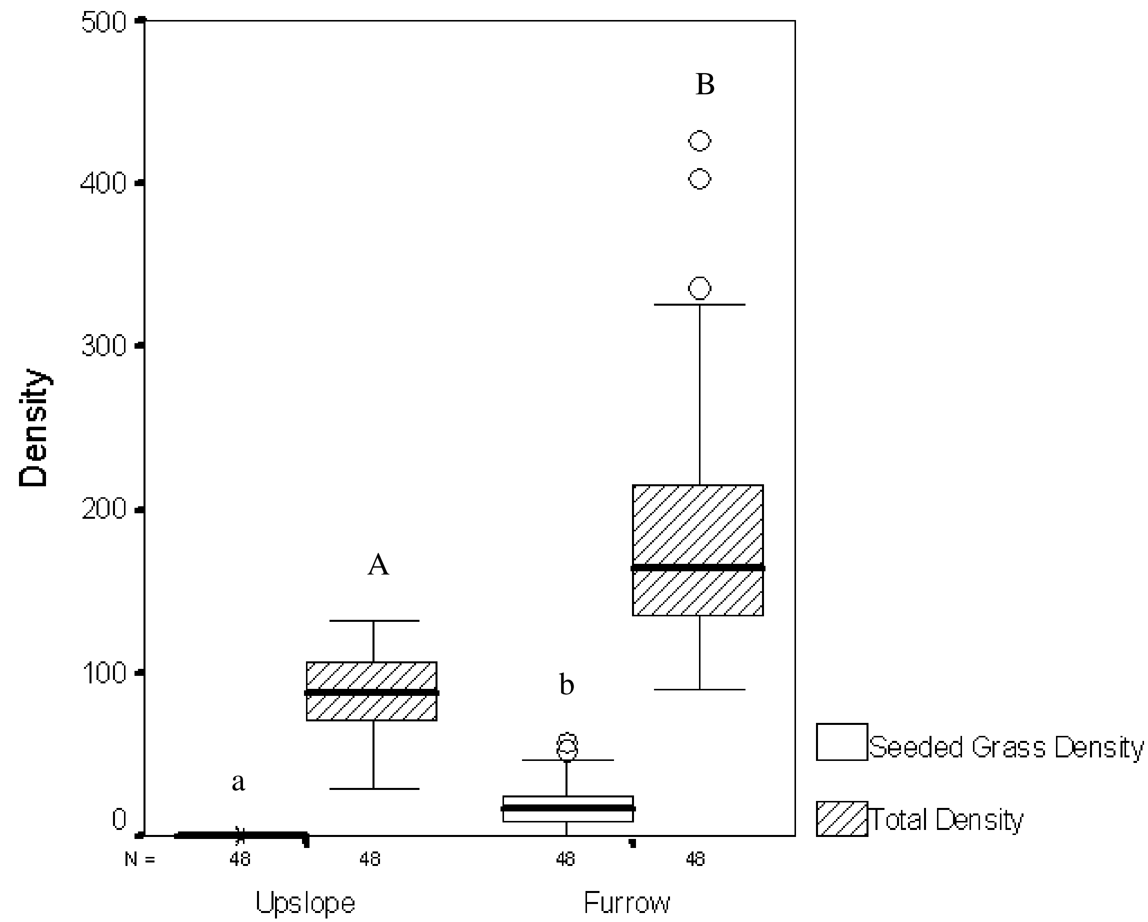

Figure 9. Box and whisker diagram showing median; 10th, 25th, 75th, and 90th percentiles; and outliers of total vegetation and seeded grass density during June 2003. Differing lowercase or uppercase letters represent significantly different means of seeded grass density or total density, respectively ($\propto = 0.05$, Bonferroni method).
Research site located in Reagan County, Texas, USA.

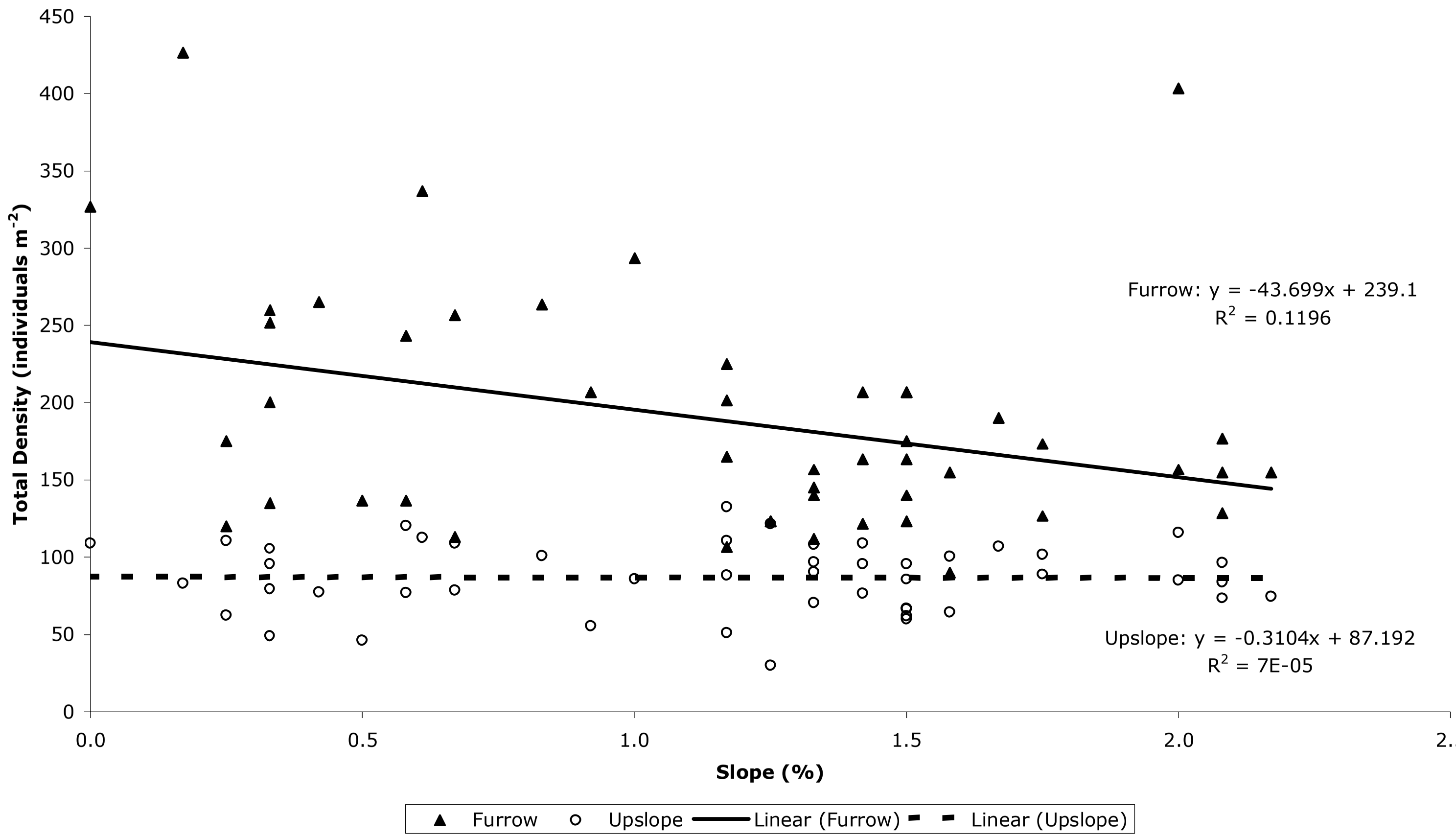

Figure 10. Total vegetation density influenced by location and slope. Lines represent best-fit lines. Data collected June 2003. Research site located in Reagan County, Texas, USA.

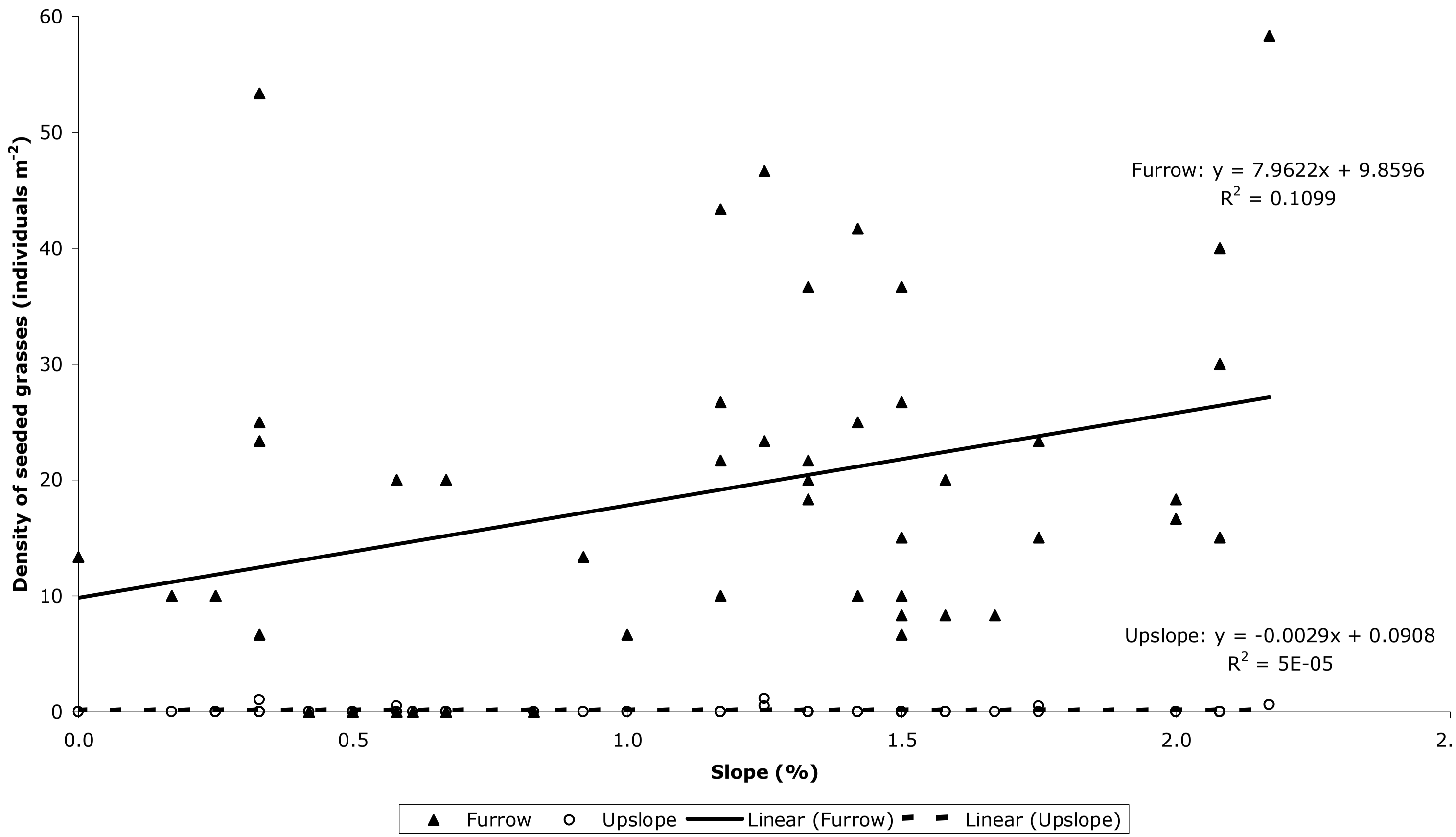

Figure 11. Seeded grass density influenced by location and slope. Lines represent best-fit lines. Data collected June 2003. Research site located in Reagan County, Texas, USA.

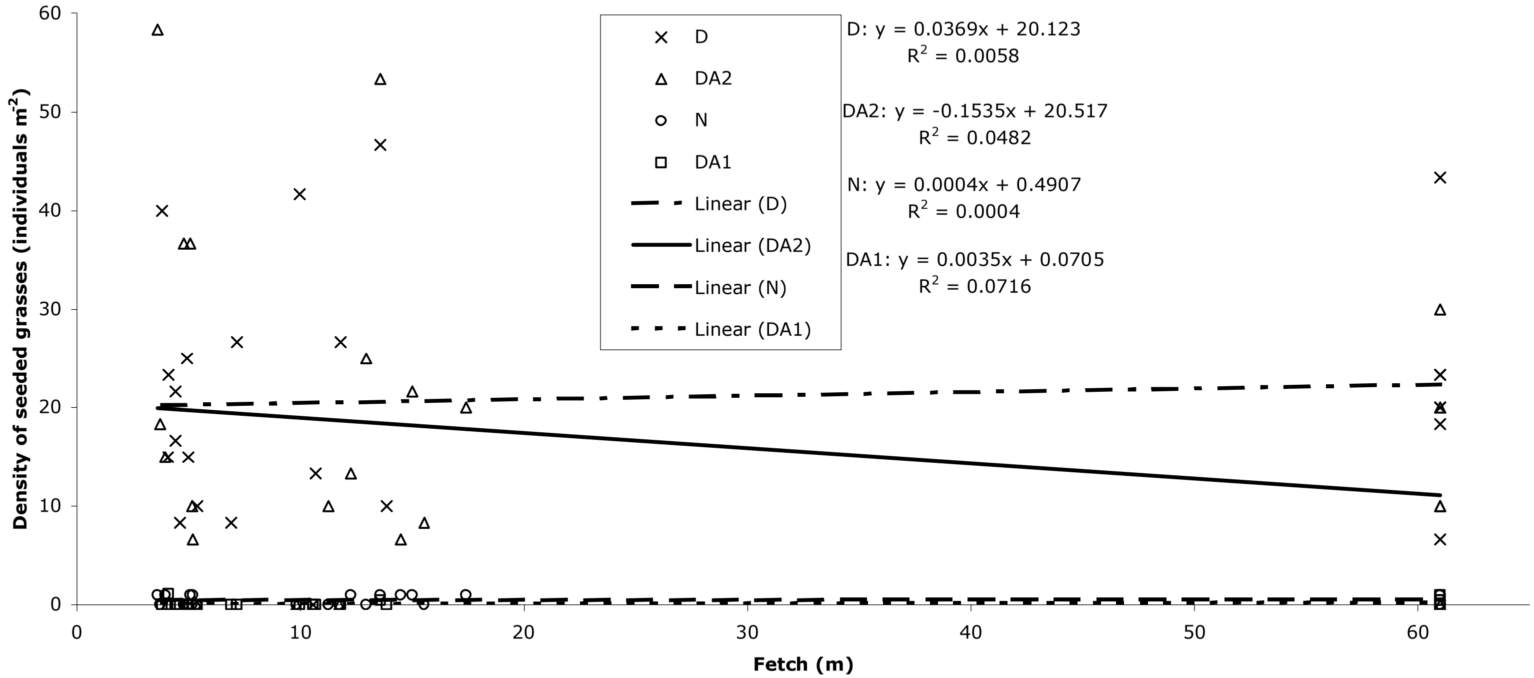

Figure 12. Density of seeded grasses as influenced by treatment and fetch. Data collected June 2003.
D= Drill 2001; DA1 = Drill 2001, Aerate 2001; DA2 = Drill 2001, Aerate 2002; N = None
Research site located in Reagan County, Texas, USA.

Tables

Table 1. Variables included in analysis of covariance model analyzing soil moisture. Profile Probe data, May 2002 – March 2003.

Soil Profile	Location (Upslope or Furrow)	Fetch	Slope	Location * Fetch	Location * Slope
0-13 cm	0.011		0.002		
0-43 cm	0.000	0.014	0.000		

Variables or interactions that are significant at $\propto = 0.05$ are noted with their F statistic's significance value (transformed data). Research site located in Reagan County, Texas, USA.

Table 2. Water holding capacity.

Pressure	Soil Profile	Location (Upslope or Furrow)	Upslope (kg kg^{-1})	Furrow (kg kg^{-1})
-33 kPa	0 – 5 cm	0.004	23.99	25.96
-33 kPa	5 – 15 cm		23.90	24.49
-33 kPa	15 – 25 cm		24.92	25.62
-33 kPa	25 – 35 cm	0.000	23.78	26.29
-33 kPa	35 – 43 cm		24.23	25.25
-1500 kPa	0 – 5 cm	0.000	11.15	13.33

Water holding capacities that are significantly different between their upslope and furrow locations at $\propto$ = 0.05 are noted with F statistic's significance value. Research site located in Reagan County, Texas, USA.

Table 3. Variables influencing vegetation density.

Density	Block	Location (Upslope or Furrow)	Treatment (D, DA1, DA2, N)	Fetch	Slope	Location * Treatment	Location * Fetch	Location * Slope	Treatment * Fetch	Treatment * Slope
Total		0.000						0.016		
Seeded Grasses		0.001	0.010					0.009	0.039	

Variables or interactions that are significant at $\propto = 0.05$ are noted with their F statistic's significance value. Data collected June 2003.
D= Drill 2001; DA1 = Drill 2001, Aerate 2001; DA2 = Drill 2001, Aerate 2002; N = None
Research site located in Reagan County, Texas, USA.

Table 4. Plant frequency of the five most common grasses and four most common forbs as characterized by their plot location (upslope or furrow).

Species	Location	Upslope Frequency	Furrow Frequency
Scleropogon brevifolius	0.000	0.31	0.00
Bouteloua curtipendula	0.000	0.00	0.07
Setaria leucopila	0.000	0.00	0.02
Elymus longifolius	0.000	0.00	0.02
Leptochloa dubia	0.000	0.00	0.01
Aphanostephus skirrhobasis		0.15	0.15
Verbena sp. 1	0.000	0.05	0.08
Erodium texanum	0.003	0.04	0.07
Verbena sp. 2		0.03	0.03

Significantly different responses are denoted with their Chi-Square statistic significance value ($\propto = 0.05$). Data collected June 2003. Research site located in Reagan County, Texas, USA.

APPENDIX B

Range of findings from soil testing laboratory.

pH	7.9 – 8.0
Nitrate	5 – 6
Phosphorus	73 - 79
Potassium	279 - 429
Calcium	75708 – 98393
Magnesium	420 – 501
Salinity	208 – 278
Sodium	339 – 359
Sulphur	121 - 128
% Sand	22 – 28
% Silt	30 – 38
% Clay	34 - 48

Elements are in ppm (available form). Soil samples are composites taken at depths of 5 – 15 cm. The water to soil ratio used in calculating the salinity was 2:1. Research site located in Reagan County, Texas, USA.

Photograph of site prior to treatment. May 2001, Reagan County, Texas, USA.

Photograph of furrow in June 2003. Reagan County, Texas, USA.

Photograph of 0.10 m^2 quadrat in furrow plot. June 2003, Reagan County, Texas, USA.

Photograph of 0.10 m^2 quadrat in furrow plot in June 2003. Reagan County, Texas, USA.

Photograph of 0.10 m^2 quadrat in upslope plot. June 2003, Reagan County, Texas, USA.

Photograph of microtopography created by drill seeder. March 2002, Reagan County, Texas, USA.

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